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Atmospheric circulation influence on the interannual variability of snow pack in the Spanish Pyrenees during the second half of the 20th century

Juan I. López-Moreno[1,2] and Sergio M. Vicente-Serrano[1]

[1]Instituto Pirenaico de Ecología, CSIC (Spanish Research Council), Campus de Aula Dei, PO Box 202, Zaragoza, E-50080, Spain

[2]Department of Geosciences, University of Fribourg, Perolles, Fribourg CH-1700, Switzerland.
E-mail: *ignacio.lopez@unifr.ch*

Abstract Large areas in the Spanish Pyrenees are covered by snow between December and April, especially above 1650 m a.s.l., the location of the cold season 0°C isotherm. However, a significant negative trend in Pyrenean snow pack was detected during the second half of the 20th century. This paper analyses the interannual evolution of snow accumulation in these mountains in relation to the variability of atmospheric circulation. The study considers two spatial scales, from weather types over the Iberian Peninsula to hemispheric atmospheric patterns. The results show strong relationships between the annual occurrence of several weather types and spring snow accumulation. Changes in the frequency of several weather types are explained by the evolution of large scale hemispheric circulation patterns, especially the North Atlantic Oscillation (NAO). Thus, the positive trend observed in the NAO index leads to a decrease in the occurrence of types that favour snow accumulation and an increase in unfavourable conditions for snow pack during the second half of the 20th century.

Keywords Iberian Peninsula; North Atlantic Oscillation; snow accumulation; Spanish Pyrenees; weather types

Introduction

In mountain areas, snow accumulation controls several environmental processes and economic activities. In particular, the availability of water resources and the seasonality of flows are closely linked to the depth and depletion of the snow pack. Several studies have analysed the impact of a possible climate change on snow accumulation and melting because of the high sensitivity of this valuable resource to climate variability (Beniston 2003; Barnett *et al.* 2005).

Many authors have stressed the great hydrological influence of snow accumulation in the Central Pyrenees (García-Ruiz *et al.* 1986; Alvera and García-Ruiz 2000; López-Moreno *et al.* 2002). López Moreno and García- Ruiz (2004) assessed that snowmelt is the main source of spring flows even more than precipitation. Thus, a large proportion of the trends in spring discharge are explained by the interannual variability of snow pack. A significant decrease in discharges (April–June) occurred for the period 1950–1999 (López-Moreno and García-Ruiz 2004). This trend cannot be explained by the evolution of spring precipitation or temperature since neither series showed temporal trends for the same period. Thus, the reduction of spring water resources must be related mainly to the decrease in winter and early spring snow accumulation detected in the second half of the 20th century (López-Moreno 2005).

The negative consequences of the decrease in snow accumulation are not only restricted to the mountainous area since the Pyrenean rivers are the main contributors of runoff to the whole Ebro Basin (Beguería *et al.* 2003; Batalla *et al.* 2004). Moreover, the irrigated lands located in the centre of the Ebro valley are supplied by Pyrenean discharges. In fact, recent changes in water resources availability are already affecting the management of Pyrenean reservoirs (López-Moreno *et al.* 2004). Furthermore, a decrease in snow accumulation could lead to considerable economic losses in tertiary activities. In the Pyrenees, the main tourist activity is centred on winter sports and annual profits are closely related to the duration and depth of snow pack.

On the other hand, it is important to know the role of atmospheric circulation on the climate variability. Different studies have found a close relationship between the temporal variability of the atmospheric circulation at the synoptic scale and the variability of the global/hemispheric atmospheric circulation patterns (Wilby *et al.* 1995; Fraedrich 1994; Stefaniki *et al.* 1998; Sheridan 2003; Pozo-Vázquez *et al.* 2005). The complex interactions between topography and the exposure to different air masses lead to noticeable differences in the response of neighbouring areas to synoptic or hemispheric circulation patterns (for the Iberian Peninsula see, for example, Goodess and Jones (2002), Corte Real *et al.* (1998), Esteban *et al.* (2005) and Vicente-Serrano and López-Moreno (2006)). This is the main reason for the biases found when global databases (i.e. Reanalysis) or outputs of General Circulation Models (GCMs) are compared with local observations (for the Iberian Peninsula see, for example, Trigo and Palutikof (2001)), especially in mountainous areas (Beniston 2003). Thus, a better understanding of the relationship between atmospheric factors and the spatial and temporal variability of climate elements is required to improve the assessment of the possible impact of climate variability and climate change at local scales.

A weather type approach is useful for analysing the evolution of diverse climate elements (Corte-Real *et al.* 1998; Twardosz and Niedzwiedz 2001; Fowler and Kilsby 2002). In particular, synoptic scale weather patterns have provided further insight into processes that contribute to snow accumulation and melting. Thus, Grundstein and Leathers (1999) and Leathers *et al.* (2002) studied the behaviour of several components of the snow-surface energy exchanges under a range of synoptic conditions over the Northern Great Plains of the United States. Changnon *et al.* (1993) and Grundstein (2003) proposed that the occurrence of distinct atmospheric circulation patterns determined the occurrence of wet and dry periods which affect the annual snow pack patterns across the Rockies.

Here, the atmospheric circulation causes of the decrease in snow accumulation in the Pyrenees are studied in order: (i) to detect the weather types that explain variability in snow accumulation; (ii) to establish whether changes in the frequency of weather types affect the evolution of the snow pack; and (iii) to relate the evolution of global and hemispheric atmospheric circulation patterns to the frequency of local weather types over the Iberian Peninsula, and hence to the trend of snow series.

The study area

The study area is located between the Aragón and Noguera Ribagorzana rivers in the Central Spanish Pyrenees (Figure 1). The altitudes increase progressively eastward and northward, where altitudes occasionally exceed 3000 m a.s.l.

Precipitation varies following north–south and west–east gradients according to the altitude and the transition from Atlantic to Mediterranean climatic characteristics (García-Ruiz *et al.* 2001). The topographic heterogeneity of the region partially explains the large spatial variability of annual precipitation. The areas above 2000 m a.s.l. receive more than 2000 mm of precipitation per year, which increases to more than 2500 mm in the

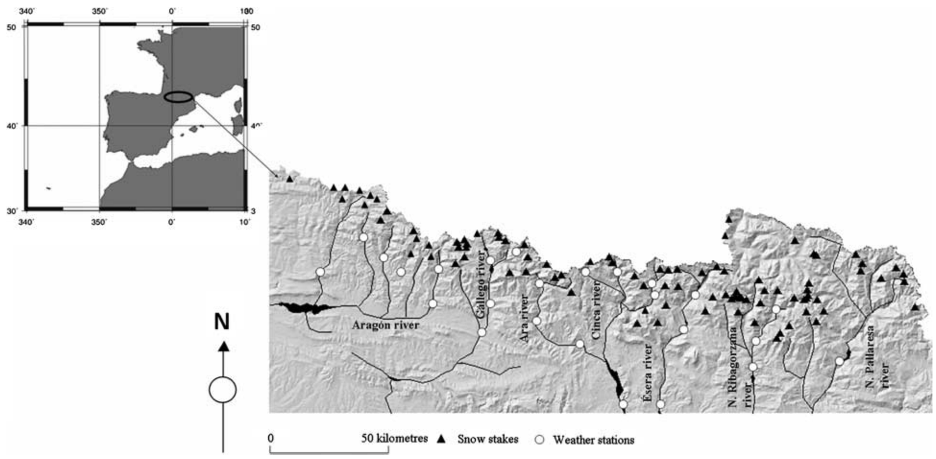

Figure 1 Study area. Location of the snow stakes and weather stations

highest divides (García-Ruiz *et al.* 2001). Most of this falls in autumn and spring. The summer is relatively dry (with occasional rainstorms), as is the winter, when snowfalls alternate with long anticyclonic periods. In the westernmost part of the study area, the winter is more humid since this zone is exposed to oceanic perturbations (García-Ruiz *et al.* 2001).

Temperatures are determined by altitude. Del Barrio *et al.* (1990) estimated a gradient of 0.6°C/100 m of altitudinal increment. Between November and April, the 0°C isotherm is around 1600–1700 m a.s.l. (García-Ruiz *et al.* 1986), representing the level above which snow accumulation occurs for a long period.

Data and methods

Snow pack and climatic data

Snow depth data were obtained from 106 snow stakes which were placed in the area in 1985. The stakes are managed by the ERHIN Programme (Estudio de los Recursos Hídricos INvernales (Study of winter water resources)), which aims to quantify the water resources related to snow accumulation in Spain. Measurements are taken regularly three times each year, although weather conditions explain slight changes in the measurement dates. In this study only the snow depths measured at the end of April or the beginning of May are considered. These dates coincide with the period in which snow pack has major hydrological implications since it is when the most intense melting period begins (López-Moreno and García-Ruiz 2004). The snow depth series showed a high correlation with the precipitation recorded between January and April and with the April temperature. These high correlations allowed the prediction of a series for spring snow packs between 1950 and 1999. Further information about the measurements and the steps required for building the snow depth series is found in López-Moreno (2005).

Precipitation and temperature data were obtained from 23 and 17 weather stations in the study area. These data were used to obtain regional indexes that summarized the variation of the variables in the whole region during the period 1950–1999 for a range of time intervals. Here we considered the precipitation series of January, February, March and April, the accumulated precipitation from January to April and the temperature series of April. These time intervals were chosen because of their capacity to predict variability in spring snow pack (López-Moreno 2005).

Weather type classification

Daily weather types over the Iberian Peninsula were obtained using the objective weather typing system of Jenkinson and Collison (1977) based on the Lamb types. The method requires information of the daily sea level pressure of the 16 points at 5° of resolution which comprise the Iberian Peninsula (Figure 2). These data were obtained from the NCEP-NCAR reanalysis data set (Basnett and Parker 1997). The Jenkinson and Collison method has been successfully used for daily weather type classification in the Iberian Peninsula (Goodess and Palutikof 1998; Spellman 2000) and its complete formulation can be consulted in Jones *et al.* (1993). The result is the discrimination of each day between 26 possible weather types: anticyclonic (A), cyclonic (C), eight directional weather types (N, NE, E, SE, S, SW, W and NW) and hybrid types between cyclonic or anticyclonic and directional (CN, CNE, CE, CSE, CS, CSW, CW, CNW, AN, ANE, AE, ASE, AS, ASW, AW and ANW).

To relate the occurrence of synoptic situations with climatic and snow series, we summarized the daily weather type series in monthly series using a similar approach to that described by Fowler and Kilsby (2002) and Corte-Real *et al.* (1998), which use the monthly sum of days of each weather type. Later, the 26 weather types were summarized in 10 types to facilitate de interpretation of the results. Following Jones *et al.* (1993) and Trigo and Da Camara (2000), the reduction was done by means of the elimination of hybrid types. When an hybrid type was found, 0.5 was added to the frequency series of cyclonic (C) or anticyclonic (A) types, and 0.5 to the correspondent directional types series (N: North, NE: NorthEast, E: East, SE: South-East, S: South, SW: SouthWest, W: West and NW: North-West). The number of days of each synoptic situation observed in the months before the snow depth measurement (from January to April) was considered in order to analyse the relationship between weather types and snow accumulation series.

We used a PCA analysis in order to synthesize the joint effect of the different weather types occurring from January to April on snow accumulation. PCA has been widely used to determine the most general temporal and spatial patterns of different climatic variables. It allows common features to be identified and specific local characteristics to be determined (Richman 1986). The PCA reduces a large number of interrelated variables to a few independent principal components that capture much of the variance of the original data set (Hair *et al.* 1998). This method permits obtaining synthetic patterns of the interannual frequency of synoptic situations, avoiding possible problems of correlation between the different weather types.

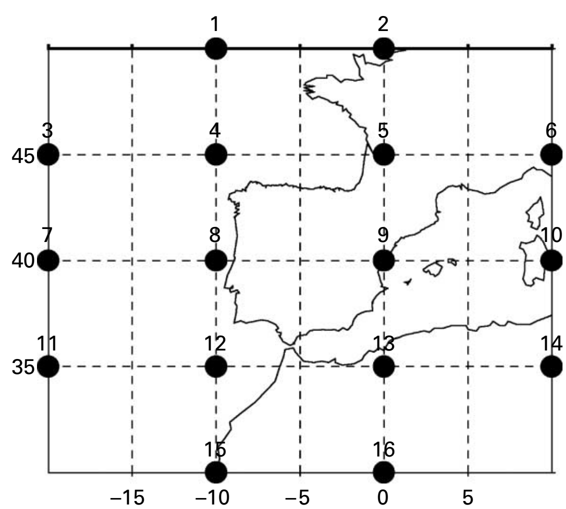

Figure 2 Grid of sea level pressure points used to classify the weather types over the Iberian Peninsula

In the performed PCA the variables are the distinct time series of the 10 weather types. A correlation matrix was selected for the analysis because it provides a more efficient representation of the variance in the data set. The criterion of component selection was accorded an eigenvalue >1 (Hair *et al.* 1998). Afterwards, components were rotated to obtain invariable spatial patterns. The rotation simplifies the spatial patterns of the studied variables (Barnston and Livezey 1987), and redistributes the final explained variance. The rotation procedure allows a clearer separation of components that maintain their orthogonality (Hair *et al.* 1998) and concentrates the loading for each PC onto the most influential variables. We used the Varimax rotation, which is the most widely applied option because it produces more stable and physically robust patterns (Richman 1986).

Global and hemispheric atmospheric circulation

The atmospheric circulation patterns at hemispheric scale have been approached by means of several teleconnection indices which, according to the literature, better explain the interannual variability of precipitation in the Iberian Peninsula (Rodríguez-Puebla *et al.* 1998, 2001; Trigo *et al.* 2004): the North Atlantic Oscillation Index (NAO), the East Atlantic pattern (EA), the East Atlantic–West Russian pattern (EA/WR) and the Scandinavian pattern (SCA). All series were obtained from the Climate Prediction Center (www.cpc.ncep.noaa.gov/data/teledoc/teleintro.html).

The relations between climate elements, weather types and teleconnection indices were assessed by means of Pearson's correlation coefficient. Temporal series were tested against linear time evolution (1950–1999) using the non-parametric Spearman's rank correlation statistic in order to detect significant temporal trends.

Results

Relation between weather types, climatic variables and snow depth series

The frequency of a given weather type over an area determines the variability of distinct climate elements (Corte-Real *et al.* 1998; Twardosz and Niedzwiedz 2001; Fowler and Kilsby 2002). Figure 3 shows some examples of strong positive and negative relationships between the inter-annual evolution of both monthly precipitation (Figures 3(a, b)) and snow series (Figures 3(c, d)) and the frequency series of a given synoptic type. Thus, precipitation in January is positively related to the frequency of west advections, and negatively with anticyclonic conditions. Likewise, there is a good relation between snow accumulation and west advections, whereas a high frequency of anticyclones clearly reduces the depth of snow pack.

Relationships between precipitation, temperature and snow depth in April with the 10 synoptic situations distinguished were checked (Table 1). Positive and significant correlations were found between the snow pack and the frequency of N, SW, W and NW weather types whilst significant negative relationships were found with the frequency of E and A types. In most cases, significant correlations with snow pack are explained by persistent relationships with precipitation in the previous months, which indicates the amount of innivation. Other types are related to April temperature which controls the melting and the phase of precipitation (solid or liquid) during that month (López-Moreno 2005). Thus, N and NW types do not explain the amount of precipitation but generate low temperatures in April, which explains the positive correlation with snow series.

PCA analysis allowed us to summarize the inter-annual variability of occurrence of the different weather types (Table 2). We selected the first 5 components, which accumulate the 76.5% of the total variance. The relative low percentage of variance explained by each component confirms the robustness of the classification method used, which provides synoptic types barely correlated. Table 3 shows the factorial loadings for each component,

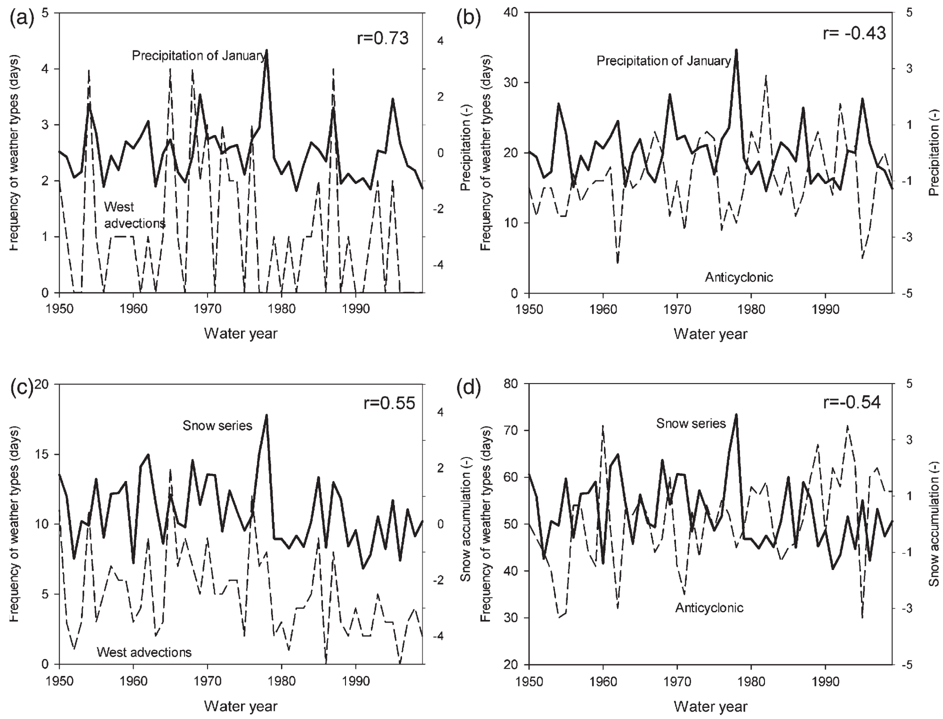

Figure 3 Evolution of precipitation and snow series related to weather type frequency. (a) Precipitation of January and days with west advections during January. (b) Precipitation of January and anticyclonic days in January. (c) Snow series and western advections from January to April. (d) Snow series and anticyclonic days from January to April

which indicate the relationship between each component and the inter-annual variability of the different weather types. Component 1 is positively correlated with W, NW, SW, N and C, whereas it is negatively correlated with A and E types. Component 2 shows positive correlations with the SE and S types and negative correlations with the frequency of N types. Component 3 shows a positive correlation with the frequency of A types, and a negative correlation with the C and E types. Component 4 stresses a high frequency of NE types, and component 5 has a similar evolution as the frequency of SE type.

The last row of Table 3 indicates Pearson's correlation coefficient between each component and the snow series. Results reveal that component 1 is closely related to the

Table 1 Correlation of the frequencies of weather types with several climate and snow series

Synoptic situation	Pp Jan.	Pp Feb.	Pp Mar.	Pp Apr.	Tª Apr.	Snow depth April
N	0.12	0.02	0.02	0.15	*** − 0.44**	***0.28**
NE	−0.23	−0.20	−0.23	*** − 0.46**	−0.05	0.02
E	*** − 0.48**	**− 0.33**	−0.17	*** − 0.37**	−0.11	*** − 0.34**
SE	*** − 0.37**	−0.19	−0.03	−0.27	***0.37**	−0.23
S	−0.01	0.04	0.04	0.07	0.18	−0.06
SW	***0.62**	***0.57**	***0.43**	0.25	***0.32**	***0.36**
W	***0.73**	***0.56**	***0.42**	***0.41**	−0.08	***0.55**
NW	***0.39**	***0.43**	***0.32**	***0.40**	*** − 0.30**	***0.34**
C	***0.33**	0.22	***0.59**	0.10	−0.16	0.23
A	*** − 0.43**	*** − 0.34**	*** − 0.62**	−0.08	−0.03	*** − 0.46**

*$\alpha < 0.05$

Table 2 Results of the Principal Component Analysis from the annual frequency series of weather types from January to December

Component	% of variance	% accumulated
1	22.2	22.2
2	16.8	39.0
3	15.5	54.6
4	11.1	65.7
5	10.9	76.5

inter-annual variability of snow pack ($R = 0.70$, $p < 0.01$), whilst the rest of the components show a very low correlation. Component 1 shows a significant negative trend over the study period ($\rho = -0.40$, $p < 0.01$; Figure 4), which indicates that the synoptic situations over the Iberian Peninsula tend to be unfavourable for snow accumulation in the Pyrenees.

The temporal evolution of the frequency of the 10 weather types (Table 4) explains the large decrease in component 1. The occurrence of several synoptic situations has changed significantly in recent decades, and most of them show significant correlations with snow accumulation. Thus, advections from SW and W, both favouring snow accumulation, show noticeable negative coefficients ($\rho = -0.40$ and $\rho = -0.34$, respectively). Otherwise, anticyclonic days tend to be more frequent ($\rho = 0.46$), which implies an increase in unfavourable conditions for snow accumulation. Other weather types did not show significant correlations with time and snow pack but high coefficients were found. These results confirm a decrease in the frequency of weather types that favour snow accumulation, whilst weather types related to low snow depths tend to increase their frequency.

The role of the general atmospheric circulation on weather types and Pyrenean snow pack

A correlation analysis between component 1 and snow series, and a range of teleconnection indices confirms the relationship between large and local atmospheric patterns and their impact on snow accumulation processes (Table 5). Only the NAO shows significant correlations. Significant correlations were found between the sign and intensity of the NAO index and several weather types between January and April (Table 6). Thus, positive relationships were found with A, which had been previously identified as an unfavourable type for snow accumulation. On the other hand, negative coefficients were observed between

Table 3 Factorial loadings of the obtained Principal Components and their correlation coefficients with snow series

	Component				
	1	2	3	4	5
A	−0.67	−0.39	0.59	−0.15	0.06
C	0.40	0.07	−0.78	−0.38	−0.11
N	0.49	−0.41	−0.04	0.42	0.47
NE	−0.10	−0.06	−0.16	0.71	−0.60
E	−0.52	0.34	−0.43	0.11	0.08
SE	−0.30	0.53	−0.13	0.24	0.62
S	−0.01	0.74	0.32	0.07	−0.27
SW	0.47	0.61	0.38	0.03	0.08
W	0.68	0.05	0.31	−0.24	−0.12
NW	0.57	−0.14	0.12	0.34	0.09
Correlation with snow series	0.71	−0.04	0.04	0.012	−0.09

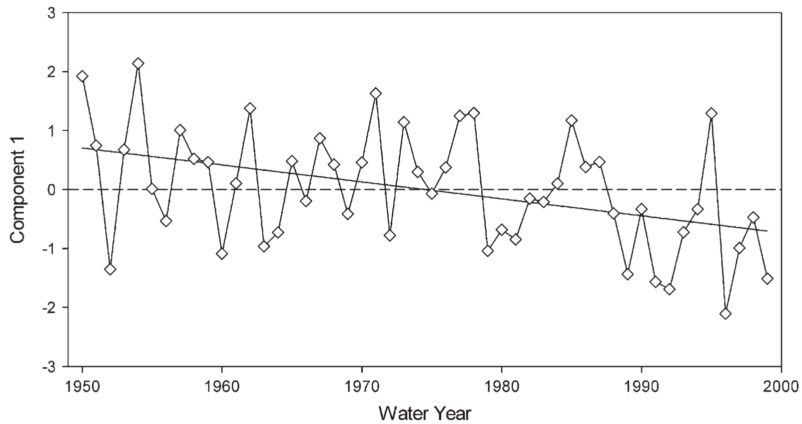

Figure 4 Temporal evolution of Component 1

the NAO and SW and W weather type series. Both types favoured snow accumulation. Thus, the increase in the NAO index observed in recent decades leads to: (i) a higher frequency of weather types unfavourable to snow accumulation; and (ii) a decrease in the occurrence of conditions that favour snow accumulation. These results explain the strong negative relationships between the NAO and component 1 and snow series (Figure 5).

Discussion and conclusions

A weather type approach has been used to analyse the relationships between large-scale atmospheric circulation patterns, local pressure fields and interannual evolution of Pyrenean snow pack.

Table 4 Temporal trends of the frequencies of weather types

Weather types	January–April
N	0.01
NE	−0.25
E	0.27
SE	0.10
S	−0.11
SW	***− 0.40**
W	***− 0.34**
NW	−0.17
C	−0.21
A	***0.46**

*$\alpha < 0.05$

Table 5 Correlation between teleconnection indices and component 1 and snow series

Teleconnection index	Component 1	Snow accumulation
NAO	**− 0.38**	***− 0.39**
EA	−0.17	0.06
EA/WR	−0.24	−0.04
SCA	0.19	0.26

*$\alpha < 0.05$

Table 6 Correlation between frequencies of weather types and NAO index

Weather type	Correlation with NAO
N	0.04
NE	0.05
E	0.12
SE	− 0.04
S	− 0.26
SW	*** − 0.44**
W	*** − 0.45**
NW	− 0.24
C	− 0.24
A	***0.42**

*α < 0.05

The main results are:

(1) There are significant correlations between the frequency of distinct weather types over the Iberian Peninsula during the months previous to the snowmelt period and the interannual variability in the snow accumulation series in the Pyrenees (Iberian Peninsula).
Several weather types, especially those related to western flows, explain the variability of winter snowfalls in the Pyrenees. It is interesting to consider that most snow stakes are located above 1700 m a.s.l. Therefore, temperature is usually below 0°C from January to March and most of the precipitation falls as snow. Snow accumulation in the lower sectors may be linked to other weather types since the west flows are related to wet but mild climatic conditions as its correlations with April temperature suggest. In April, temperature controls both the precipitation phase and the melting processes, especially in sectors below 2200 m a.s.l. (López-Moreno 2005). This explains why some weather types, which show a strong correlation only with April temperature (N and NW with negative sign), also have a significant relation with snow series.

(2) From a Principal Component Analysis, the first component has shown a strong relationship with the snow pack evolution. Thus, this component allowed us to

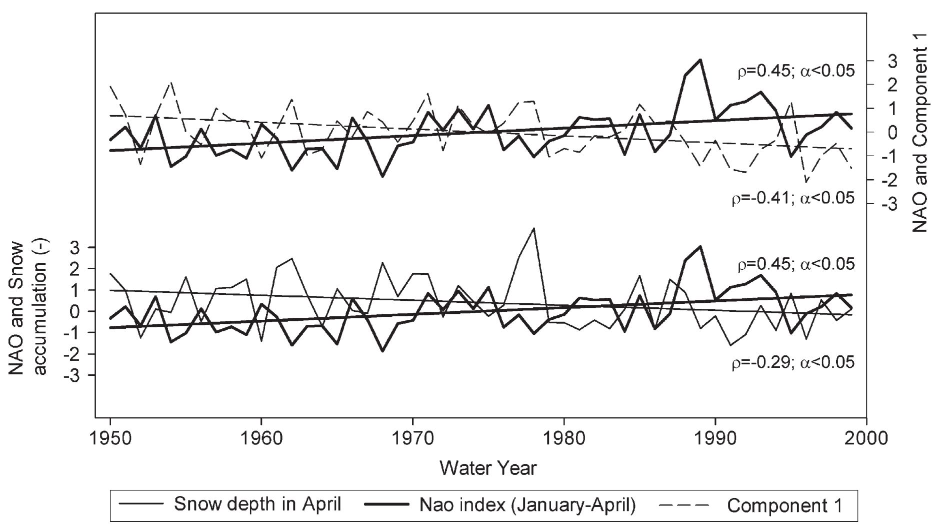

Figure 5 Temporal evolution of the NAO index, Component 1 and snow series

establish whether a given year was favourable or unfavourable for snow accumulation according to the frequency of weather types. Component 1 represents the evolution of some weather types that show a negative trend in their frequency but favouring snow accumulation (West flows and Cyclonic types). It leads to a progressive increase in unfavourable atmospheric conditions for snow accumulation.

(3) Our results show that the frequency of many weather types between January and April over the Iberian Peninsula respond significantly to the NAO index. Most of the types significantly correlated with the NAO were previously identified as conditions highly related to snow series. Positive correlation has been found between the NAO and the frequency of the anticyclonic types, whilst negative coefficients were detected for the SW and W types (both favourable for snow accumulation). These results agree with the negative correlation obtained between the NAO and component 1 and snow series. Other large-scale atmospheric circulation patterns over the Northern Hemisphere do not show significant correlations with Pyrenean snow series. The mechanisms by which the distinct phases of the NAO produce these effects on the frequency of synoptic situations over the Iberian Peninsula has been described by several authors (Rogers 1997; Rodriguez Puebla *et al.* 2001; Martin-Vide and Fernández 2001). During winters with high NAO values, the Iberian Peninsula is highly influenced by the Azores Anticyclone, and depressions associated with the Polar front tend to be blocked. This situation has been dominant over long periods during recent decades as a consequence of the positive trend of the NAO (January–April).

The relationship between trends in the local atmospheric circulation patterns and the evolution of snow pack has been observed in other areas (Changnon *et al.* 1993; Dettinger and Cayan 1994; Huth 2001; Grundstein 2003). Several authors also agree that changes in the local pressure fields are a response to variability of large-scale atmospheric circulation patterns (i.e. Rogers 1997; Corte-Real *et al.* 1998; Bednorz 2002, 2004). In particular, several references consider that the NAO explains most winter climate variability in the North Atlantic region (Lamb and Peppler 1987; Hurrell 1995; Hurrell and Van Loon 1997; Trigo and Palutikof 2001).

Our study highlights the high correlation between the evolution of the climatic elements in the Pyrenees and synoptic situations over the Iberian Peninsula, which depends on wider scale atmospheric modes. These results confirm that the decrease in snow pack is a response to hemispheric atmospheric circulation. Thus, Pyrenean snow pack exhibits a similar evolution to that of other mountain areas in Southern Europe, which have shown sensitive to the inter-annual evolution of the NAO index (Martin *et al.* 1994; Beniston 1997, 2003; Breiling and Charamza 1999; Beniston *et al.* 2003).

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